Cherenkov Radiation From Jets in Heavy-ion Collisions

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What is Cherenkov Radiation?

- The emission of photons in a dielectric medium by particles traveling with a velocity faster than the phase velocity in the medium
- The angle of emission is given by:

$$\cos\theta_c = \frac{1}{n\beta}$$

Conditions for Cherenkov Radiation

- The incident particle must couple to a specific radiation field
- The radiation field must be modified inside the medium due to multiple scattering from its constituents
- The projectile must move with $v > v_p$
- Equivalently, with a kinetic energy of

$$T_{threshold} = m_p \left\{ \left[1 - v_p^2(\omega) \right]^{-1/2} - 1 \right\}$$

D.B. Ion and W. Stocker, Phys. Lett. B, **311**, 339-342 (1993).

Cherenkov Radiation as a Diagnostic Tool

- Insight into internal structure of nucleons
- Nuclear projectiles that lose energy upon entering a nuclear medium because of density effects will always yield a coherent response from the medium in the form of radiation (photons, pions, etc.)
- Yields information concerning the nature of confinement
- Probe the resonance structure of dense matter through production of Cherenkov-like soft hadrons along the path of quenched jets

D.B. Ion and W. Stocker, Phys. Lett. B, **258**, 3, 4 (1991).
V. Koch, A. Majumder, and Xin-Nian Wang, Phys. Rev. Lett. **96**, 172302 (2006).

Angular Distribution of Soft Hadrons (1)

- In vacuum, soft hadrons are emitted along the direction of the jet
- In our case, these hadrons are emitted at a distinct angle with respect to the jet
- Caused by normal gluon bremsstrahlung as a result of parton scattering → hadronization of radiated gluons

V. Koch, A. Majumder, and Xin-Nian Wang, Phys. Rev. Lett. **96**, 172302 (2006).
A. Majumder, and Xin-Nian Wang, Phys. Rev. C **73**, 051901 (2006).

Angular Distribution of Soft Hadrons (2)

- To find the cone size, write the gluon's dielectric constant as:

$$\varepsilon(\ell) \equiv 1 - \frac{\Pi_T(\ell)}{\left(p^0\right)^2}$$

the cone size of the Cherenkov-like gluon radiation is

$$\cos^2\theta_c = z + \frac{1-z}{\varepsilon(\ell)}$$

with $\ell = \left(p^0, \vec{p}\right)$

A. Majumder, and Xin-Nian Wang, Phys. Rev. C **73**, 051901 (2006).

Index of Refraction and Coherent Gluon Scattering

- A large index of refraction corresponds to a spacelike dispersion relation; allows for Cherenkov-like gluon bremsstrahlung
- This can result only from coherent gluon scattering off of partonic bound states in the quark-gluon plasma (QGP)
- Method of determining bound states within the QGP

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Bound States in the QGP

- Bound states can have excitations, stimulated by simple resonant scattering via gluon interactions
- The scattering amplitude is attractive for gluon energies lower than the first excited state, implying an attractive optical potential
- This yields a spacelike gluon dispersion relation, and Cherenkov radiation will occur
- The interaction Lagrangian that describes this is

$$\mathscr{L} = \frac{1}{2}\sum_{i=1}^{2}\left(\partial\phi_i\right)^2 + \left(\partial\Phi\right)^2 + \frac{1}{2}\sum_{i=1}^{2} m_i^2\phi_i^2 + 2g\Phi\phi_1\phi_2$$

V. Koch, A. Majumder, and Xin-Nian Wang, Phys. Rev. Lett. **96**, 172302 (2006).

The Dispersion Relation (1)

- The gluon propagator is

$$D^{\mu\nu}(\ell) = -\frac{P_T^{\mu\nu}}{\ell^2 - \Pi_T + i\varepsilon} - \frac{P_L^{\mu\nu}}{\ell^2 - \Pi_L + i\varepsilon}$$

where $P_T^{\mu\nu}$ and $P_L^{\mu\nu}$ are the transverse and longitudinal projectors

- For spacelike gluon dispersion relations, focus on transverse part

A. Majumder, and Xin-Nian Wang, Phys. Rev. C **73**, 051901 (2006).

The Dispersion Relation (2)

- The dispersion relation from the previous equation is

$$\ell^2 - \Pi(\ell) = 0$$

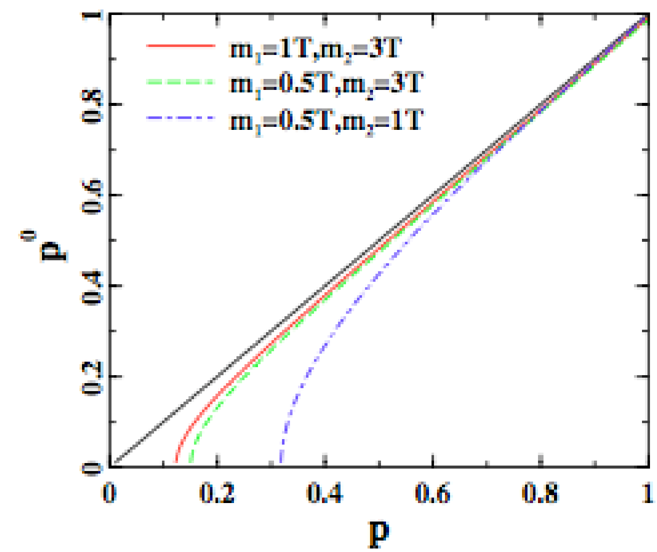

FIG. 3 (color online). The dispersion relation of Φ in a thermal medium with transitional coupling to two massive particles. The diagonal line represents the light cone.

V. Koch, A. Majumder, and Xin-Nian Wang, Phys. Rev. Lett. **96**, 172302 (2006).

The Dispersion Relation (3)

- Spacelike dispersion for low momentum
- Dispersion depends on the masses of the bound and excited states only
- Based on the spread in momentum, we may be able to determine the mass of the bound states of the QGP

Relation of Cherenkov Radiation and Gluon Momentum

- From the dispersion relation, there is a strong dependence of the Cherenkov-like bremsstrahlung on the momentum of the radiated gluon
- Thus the angular displacement of the soft hadrons with respect to the jet will go to zero with increasing gluon momentum

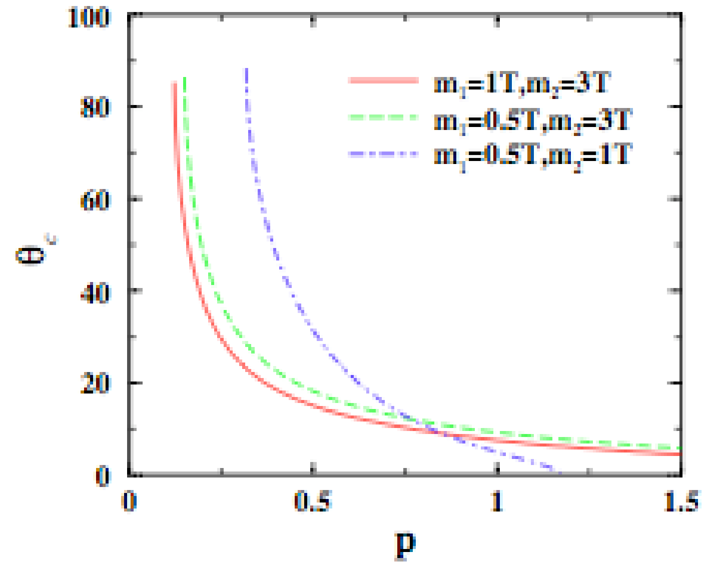

FIG. 5 (color online). Dependence of the Cherenkov angle on momentum of the emitted particle.

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Quark Energy Loss (1)

- The energy loss due to Cherenkov-like gluon radiation can be calculated from

$$\Delta E = E\int dz\,d\ell_T^2\, z\,\frac{dN_g}{dz\,d\ell_T^2} \approx \Delta E_0 \times \begin{cases} 2 & \text{for } \dfrac{|\Pi_T|L}{2E} \gg 1 \\ 1+\dfrac{1}{3}\dfrac{|\Pi_T|L}{2E} & \text{for } \dfrac{|\Pi_T|L}{2E} \ll 1 \end{cases}$$

with $$\frac{dN_g}{dz\,d\ell_T^2} \approx P(z)\frac{\alpha_s^2\tilde{C}L}{m_N}\frac{1}{\left[\ell_T^2+(1-z)\Pi_T(\ell)\right]^2}\left[1-e^{-\left(L/\tilde{\tau}_f\right)^2}\right]$$

A. Majumder, and Xin-Nian Wang, Phys. Rev. C **73**, 051901 (2006).

Quark Energy Loss (2)

$\Delta E_0 \approx 3\tilde{C}\alpha_s^2 m_N L^2 \ln\left(E/\mu\right)$ is the radiative energy loss from normal gluon bremsstrahlung

μ is the averaged transverse momentum transfer for elastic parton scattering

$P(z) = \frac{1}{z}\left[1 + (1-z)^2\right]$ is the quark-gluon splitting function

$\tilde{\tau}_f = 2z(1-z)\,E/\ell_T^2$ is the gluon formation time

Quark Energy Loss (3)

- The total energy loss is twice that for normal gluon radiation when

$$\left|\Pi_T\left(p^0\right)\right| \gg {}^{2E}\!/_{L}$$

- This corresponds to a large gluon dielectric constant,

$$\varepsilon \gg 1 + \frac{2}{z^2} EL$$

- Thus, the dielectric property of the medium increases the induced radiative energy loss

A. Majumder, and Xin-Nian Wang, Phys. Rev. C **73**, 051901 (2006).

Conclusions

- Cherenkov radiation is largely dependent upon the radiated gluon momentum, which gives insight into the mass of the bound states of the QGP
- The cone size θ_c will get smaller with increasing gluon momentum
- The total parton energy loss increases by a factor of 2 for a large dielectric constant, which in turn affects the hadron spectra due to fragmentation of leading partons
- Cherenkov-like bremsstrahlung explains the emission of pattern of soft hadrons via the dispersion relation

References

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